Distribution of Suspended Matter in the Panama Basin

WILLIAM S. PLANK, J. RONALD V. ZANEVELD, AND HASONG PAK

School of Oceanography, Oregon State University, Corvallis, Oregon 97331

The distribution of suspended matter in the Panama basin was determined by means of light scattering and Coulter counter measurements on water samples collected at 50 hydrographic stations. The observed distribution indicates three probable sources of suspended matter: (1) the surface waters throughout the basin; (2) erosion and runoff from the continents; and (3) bottom erosion at two sites on the Carnegie Ridge. The distribution of suspended matter also confirms in most respects the pattern of abyssal circulation proposed by Norman P. Laird (1971).

The Panama basin, bounded by the Carnegie and Cocos ridges and the coasts of Panama, Columbia, and Ecuador, has been the subject of an increasing number of oceanographic studies in recent years. The circulation of the surface and intermediate layers has been described by *Stevenson* [1970] and *Wyrtki* [1967]. *Laird* [1969, 1971] has hypothesized a model for abyssal circulation in the basin based on observations of hydrographic properties. Studies of sediment distribution [*van Andel et al.*, 1971; *Kowsmann,* 1973; *Moore et al.*, 1973; *van Andel*, 1973] have also provided information that has implications for the abyssal circulation in the basin.

During November and December 1971 we conducted a program of optical measurements in the Panama basin in order to delineate the distribution of suspended particulate matter in the basin. We hoped to use this distribution, along with hydrographic and current meter measurements, to gain further insight into the abyssal circulation and the sources and sinks of particulate matter in the basin.

Laird [1969] hypothesized a single source for the bottom water in the basin: the pass over the Carnegie ridge near the coast of Ecuador, which has a sill depth of about 2500 meters. The distribution of near-bottom potential temperatures indicates that after entering the basin through this pass some of the water continues northward, parallel to the coast, filling several subbasins off the coast of Columbia. The remaining water turns to the west, passes between the Malpelo and Carnegie ridges, and then spreads northward filling the subbasins west of the Malpelo Ridge. The distribution of oxygen and salinity in the near-bottom water supports this overall pattern of circulation.

An examination of the bathymetry of the ridges surrounding the basin indicates that another likely route for water entering the basin would be through the saddle over the Carnegie Ridge, which is at about 85°W and has a sill depth of about 2300 meters. Laird's studies of hydrographic properties did not point to this saddle as a source of bottom water. However, a study of the sediment cover in the basin [*van Andel et al.*, 1971; *Kowsmann,* 1973; *Moore et al.*, 1973] showed that this saddle is an area of active erosion and that products of the erosion are found along the north side of the ridge. Since the distribution of suspended particulates has been utilized in several cases as an indicator of deep circulation [*Jerlov*, 1959, 1968; *Hunkins et al.*, 1969; *Ewing et al.*, 1970; *Ichiye et al.*, 1972], the implication of bottom erosion by northward-flowing currents led us to believe that a study of suspended matter in the basin might be useful in evaluating this saddle as a source of bottom water in the basin.

Several techniques have been used to measure the concentration of suspended matter, each of which has its limitations. Large numbers of measurements have been made by filtering or centrifuging water samples collected by sampling bottles varying in size from 5 liters up to hundreds of liters [*Lisitzin*, 1972; *Ewing and Thorndike,* 1965]. The difficulties with this method are obvious: to obtain accurate measurements, especially in the extremely clear waters found at great depths, large samples are necessary, but the larger the samples, the more cumbersome and time-consuming they are to handle and analyze, and the greater is the likelihood of contamination. A modification of the filtration method that appears to hold promise is the technique of in situ filtration. This method is slow, but accuracy can be improved as much as necessary by pumping for longer times. Another technique for measuring suspended matter that has been used a great deal is the measurement of an optical property such as light attenuation or scattering [*Burt*, 1957; *Jerlov*, 1955; *Thorndike and Ewing*, 1967; *Ochakovsky*, 1966]. The difficulties involved in calibrating one such technique have been discussed by *Beardsley et al.* [1970]. In general, it appears that such techniques may be most useful for rapid surveys of large areas, and that for very accurate measurements of the concentration of suspended particles or of the particle size distribution, other methods may be preferable. In this study, two techniques were utilized to obtain information on the suspended matter; measurements of light scattering and measurements of the particle sizes by means of a Coulter counter.

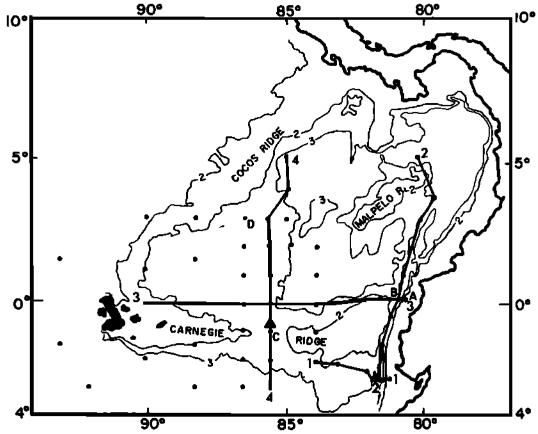

Fig. 1. Bathymetry of the Panama basin [generalized after *van Andel et al.*, 1971]. Stations are indicated by black dots. Letters A, B, C, and D show locations of profiles in Figure 2. Cross sections in Figures 3 through 6 are indicated by lines 1-1 through 4-4. Current meter locations are indicated by triangles. Bathymetric contours are in kilometers.

EXPERIMENTAL PROGRAM

Our study was conducted during the 1971 cruise of the RV *Yaquina* to the Panama basin. At each of the 50 stations shown in Figure 1 hydrographic casts were made, usually to within 15 meters of the bottom. The water samples

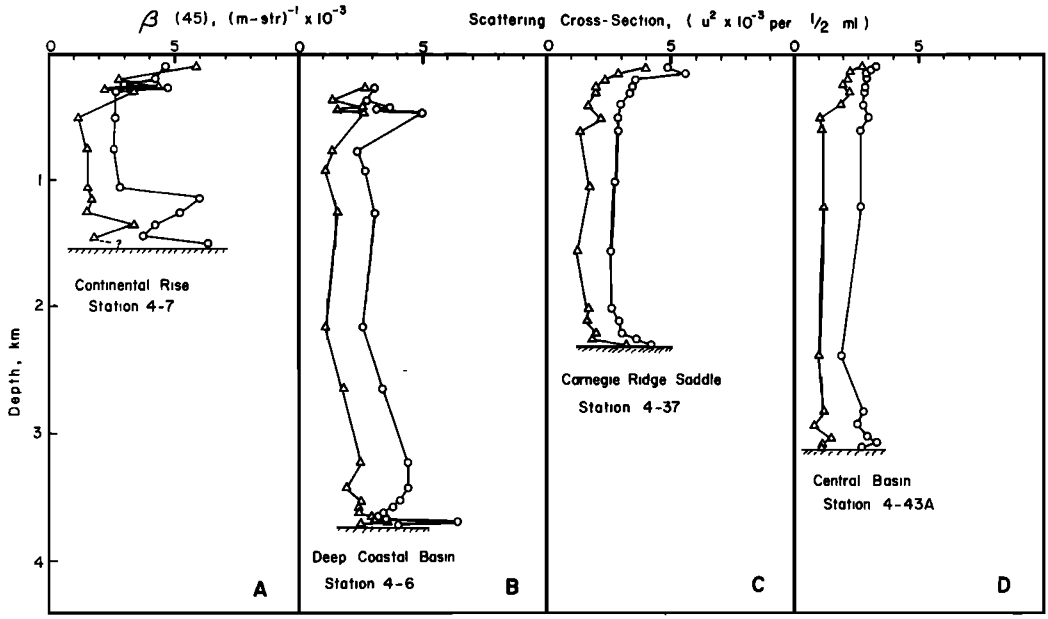

Fig. 2. Profiles of light scattering at 45° and scattering cross section of suspended particles at locations A, B, C, and D in Figure 1. Circles denote light scattering values. Triangles denote cross section values. Units of abscissa apply to both parameters.

obtained were analyzed for light scattering and particle content, in addition to temperature, oxygen content, salinity, and the concentrations of several nutrients.

The use of the Coulter counter in oceanographic applications has been discussed extensively [*Carder*, 1970; *Sheldon and Parsons*, 1967]. Briefly, the instrument measures the height of an electronic pulse generated by the passage of a suspended particle through a small orifice. The height of this pulse has been shown to be proportional, within certain limits, to the volume of the particle. In this paper 'particle diameter' means the diameter of a sphere having the same volume as that measured by the instrument.

Particles with diameters as small as 0.4 μm can be measured with the Coulter counter. However, in the interests of rapidity and ease of analysis it was decided to utilize a 100-μm orifice, which allows measurement of particles down to about 2 μm. The cumulative size distribution of particles was determined at four diameters: 2.22, 3.53, 5.60, and 10.22 μm. The volume concentration of particulate matter over this range of sizes was obtained by numerical integration, and it is this parameter which is plotted in Figures 3, 4, 5, and 6. Several investigators [*Bader*, 1970; *Plank et al.*, 1972; *Sheldon et al.*, 1972] have found the relative size frequency distribution of particulate matter in sea water to be almost constant, especially if only samples collected below about 300 meters are considered. The size distributions of the particles we examined were found in almost all cases to be nearly exponential in shape. We thus feel that an assumption of constant relative size-frequency distribution is a good one. Measurements of the concentration of particles between 2.2 and 10.2 μm are then proportional to the total concentration of suspended matter. The proportion of the total concentration represented is difficult to determine, however, as it depends on the upper limit of sizes that one assumes to exist in the sample and also on the shape of the size distribution in the submicron range.

Light-scattering measurements were made on the same samples that were analyzed in the Coulter counter in order to obtain an independent measure of relative particle concentration. The scattering of light having a wavelength of 436 nm at 45° from the forward direction [$\beta(45)$] was measured with a Brice-Phoenix light-scattering photometer. The relationship between light scattering and particle concentrations in the deep sea has been discussed by *Pak et al.* [1971] and *Beardsley et al.* [1970]. In general, if the suspended matter is fairly uniform in composition and size distribution, the light-scattering measurements should be linearly related to total particle concentration. These conditions should apply at depths greater than about 300 meters. At the two locations indicated by triangles in Figure 1, currents

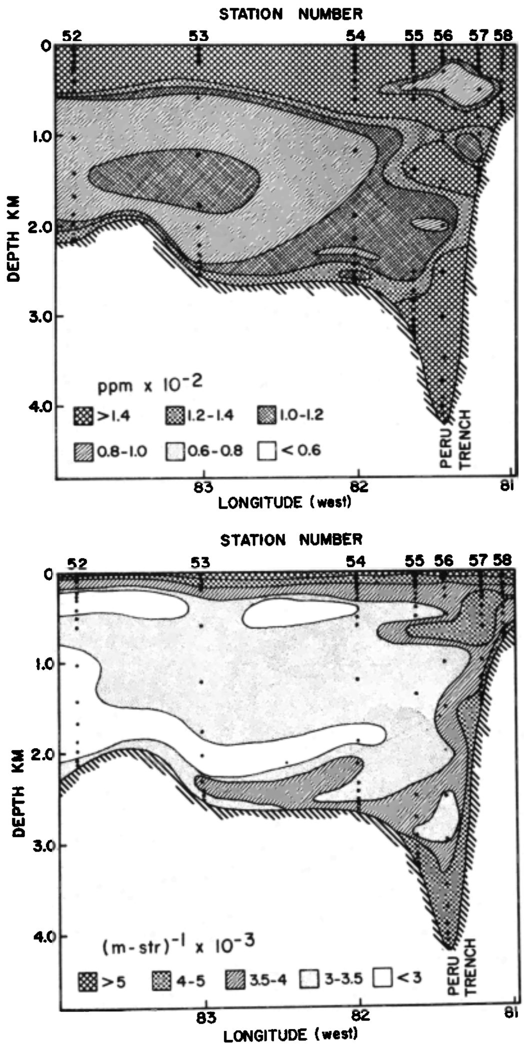

Fig. 3. Cross sections of the concentration of particles between 2.2 and 10.2 μm in ppm $\times$ 10^{-2} by volume (upper) and light scattering at 45° in $(m\ str)^{-1}$ $\times$ 10^{-3} (lower) along line 1-1 in Figure 1.

were measured 1 meter from the bottom in an attempt to gain some information about current speeds and directions near the two low points on the Carnegie Ridge.

Results

Profiles of light scattering and particle concentration from the four locations marked A through D in Figure 1 are plotted in Figure 2. These profiles are intended to indicate the general shape of profiles found in the various types of topographic provinces in the area we are studying and to indicate the degree of correlation found between measurements of light scattering and particle concentration. The particle concentration parameter in Figure 2 is geometric cross section (sometimes referred to as scattering cross section), which is proportional to the ⅔ root of particle volume. The values on the abscissa represent the projected cross-sectional area of the particulate matter between 2.22 and 10.22 μm in diameter contained in ½ ml of seawater (the size of the sample analyzed in the Coulter counter). This parameter has been previously used in studies of the correlation of light scattering and suspended particle concentration [*Beardsley et al.*, 1970]. Note that the values on the abscissa in Figure 2 apply to both parameters.

Figures 3, 4, 5, and 6 are cross sections of

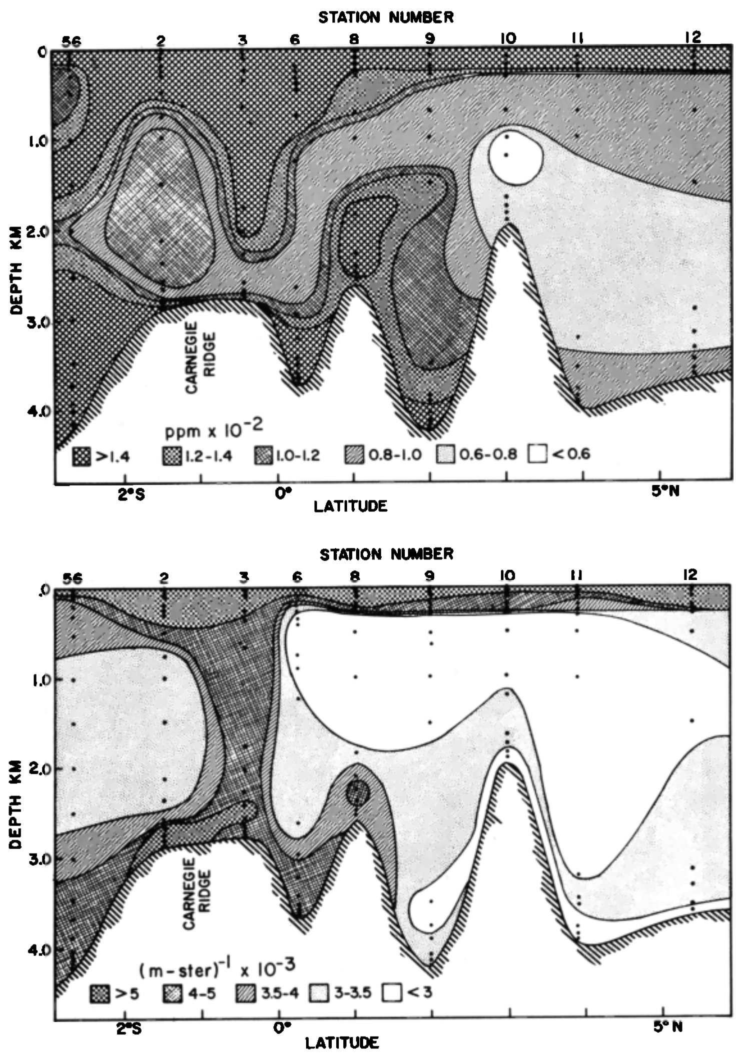

Fig. 4. Cross sections of the concentration of particles between 2.2 and 10.2 μm in ppm × 10^{-2} by volume (upper) and light scattering at 45° in (m str)$^{-1}$ × 10^{-3} (lower) along line 2-2 in Figure 1.

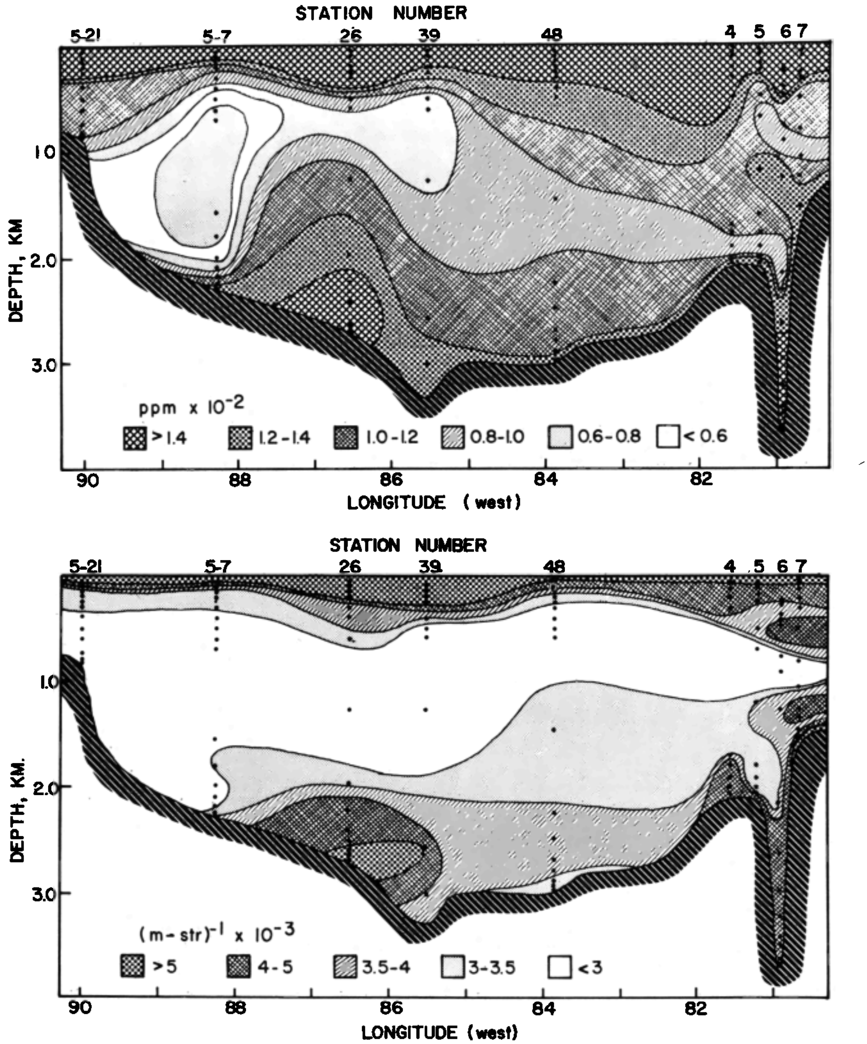

Fig. 5. Cross sections of the concentration of particles between 2.2 and 10.2 μm in ppm $\times$ 10^{-2} by volume (upper) and light scattering at 45° in (m str)$^{-1}$ $\times$ 10^{-3} (lower) along line 3-3 in Figure 1.

light scattering and particle concentration along the lines marked 1-1 through 4-4 in Figure 1. Particle concentrations on these cross sections are shown in units of ppm $\times$ 10^{-2} by volume. For comparison with other authors whose results are reported in terms of mass concentration, we should note that, for an assumed particle density of 2.75 g/ml (the density of clay particles), 1 ppm by volume equals 2.75 mg/l.

Figure 7 shows contours of integrated particle volume in the lower 100 and 500 meters of the water column. The values are obtained by numerically integrating the volume of particulate matter from the bottom to 100 and 500 meters above the bottom. The contour value represents the amount of particulate matter, in cubic microns, contained in a column of water ½ cm^2 in cross-sectional area and 100 meters high (for the upper figure; 500 meters high for the lower).

DISCUSSION

It is interesting to compare the volume concentrations of particles we measured with concentrations obtained by other workers who have made measurements over a wider range of sizes or who have used other techniques to obtain particle concentrations.

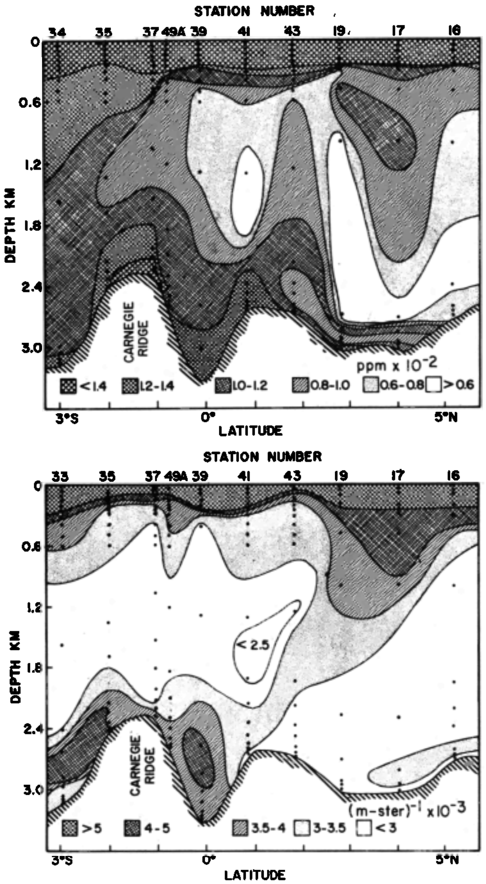

Fig. 6. Cross sections of the concentration of particles between 2.2 and 10.2 μm in ppm $\times$ 10^{-2} by volume (upper) and light scattering at 45° in (m str)$^{-1}$ $\times$ 10^{-3} (lower) along line 4-4 in Figure 1.

Sheldon et al. [1972] determined volume concentrations between diameters of 1 and 100 μm by means of a Coulter counter over a wide range of depths and in several areas of the world. At 500 meters the volume concentrations they obtained varied from about 0.03 to 0.15 ppm. At 5000 meters the minimum concentrations they found were less than 0.02 ppm.

If, as Sheldon found, particle size spectra in deep waters show roughly equal amounts of material in logarithmically equal-sized intervals, then our measurements between 2.2 and 10.2 μm should amount to about 34% of their measurements between 1 and 100 μm for water with the same total concentration of particles. Our measurements at 500 meters averaged about 0.012 ppm to 0.014 ppm, and the minimum concentrations in deeper waters decreased to less than 0.006 ppm. Considering the difference in the size ranges examined, our measurements are then not inconsistent with those of *Sheldon et al.* [1972].

In a study of suspended matter in the Caribbean Sea utilizing a gravimetric analysis, *Bassin et al.* [1972] filtered water from 5- and 30-liter Niskin bottles and obtained minimum mass concentrations (at depths of about 3 km) of less than 50 μg/l. This is equivalent (for an assumed particle density of 2.75 g/ml) to a volume concentration of 0.018 ppm. This value compares well with the values obtained by both Sheldon and us (assuming our measurements

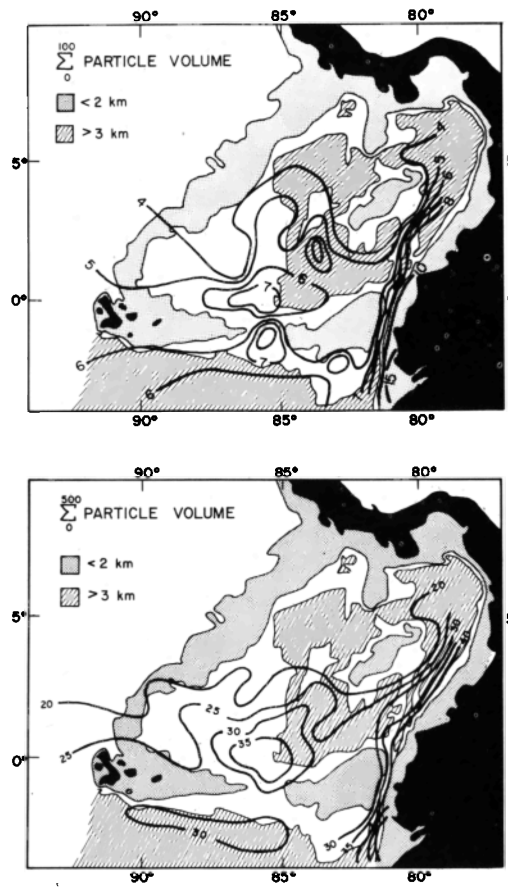

Fig. 7. The integrated volume of suspended particles between 2.2 and 10.2 μm in the lower 100 meters of the water column (upper) and the lower 500 meters of the water column (lower). Units of the contours are 2 μm^3 $\times$ m/ml.

are equivalent to 34% of Sheldon's), although any comparison of gravimetric and Coulter counter results is, of course, complicated by the different size range of particles examined by the two methods. These comparisons indicate that our measurements over a narrow size range are not only valid in a relative sense, but are also valuable in indicating roughly the magnitude of the total amount of suspended matter present.

The cross sections of Figures 3–6 show that high concentrations of suspended matter occur primarily in four locations:

1. In the surface layers throughout the basin.
2. Over the Carnegie Ridge in the two north-south sections (Figures 4 and 6). These high concentrations seem to occur throughout a greater range of depths in the section near the coast (Figure 4).
3. On the east-west section in Figure 5, in the intermediate and deep waters near the coast and between 86°W and 88°W, to the northwest of the saddle.
4. Near the bottom in the Peru trench (Figure 3) and in the deep coastal basin to the north of the Carnegie Ridge (Figure 4).

Three probable sources of the suspended matter found in the basin are thus indicated:

1. The surface layers throughout the basin contribute particles that may settle through the water column to the bottom.
2. The continent supplies material by runoff and erosion on the shelf. The particle 'clouds' near the coast between about 300 and 1300 meters in Figure 3 may indicate that the Guayas River, located at the same latitude as this section, is an important source of suspended particles.
3. Bottom erosion in the saddle at 85°W and probably also in the pass near the coast is injecting particles into the water column. The current meter measurements taken at the locations shown in Figure 1, although not of sufficient duration (6–7 hours) to determine the long-term circulation, did show velocities between 7 and 10 cm/sec 1 meter above the bottom. Considering the fact that, with such a short record, the probability of seeing maximum velocities is very small, it is likely that velocities high enough to erode bottom sediments do occur at these sites, and, as has been discussed previously, sediment samples indicate that this is the case. Current direction was predominantly aligned with the axes of the two passes, and in both cases 180° reversals occurred, indicating that the currents have a tidal component. It is probable that these two passes are sites of advective and diffusive processes of sufficiently high energy to erode and maintain in suspension increased amounts of particulate matter.

The presence of higher concentrations of particles throughout most of the water column over the Carnegie Ridge that we see in Figure 4 may be a result of the confluence at this point of all three sources of suspended matter. That is, settling from the surface, erosion, and runoff from the shelf and bottom erosion in the vicinity of the sill at about 1°S latitude all contribute particles to the water column near station 3, resulting in high concentrations from the surface to the bottom. High concentrations near the bottom both to the north and south of the Carnegie Ridge is this cross section may be a result of the erosion of particles from the saddle by the oscillatory currents mentioned above. The particles may then be transported to the north and south by gravity or advection or both.

The profiles in Figure 2 show that on the continental rise (location A) and near the saddle at 85°W (location C) there are well-developed nepheloid layers near the bottom, as might be expected if active erosion is occurring. In the deep coastal basin (location B) the increase in particle concentration is smaller in magnitude and is spread over a greater depth. The profiles from the central basin (location D) demonstrate the characteristics of an area where there is probably little erosion or sedimentation taking place in the size ranges of particles we examined. Values of light scattering and particle concentration are low and relatively constant below 400 meters.

In Figure 7 the contours of integrated particle volume show a high gradient near the coast. This indicates, first, that the continent is a major source of particulate matter and, second, that much of this matter is being deposited in the deep coastal basin. The contours also show regions of high particle content centered around the Carnegie Ridge saddle at 85°W. It appears that material eroded from the sill is probably being spread both to the north and the south and is settling out of the water column on the flanks of the ridge. The contours in Figure 7 also indicate tongues of suspended particles extending into the northwest portion of the basin. Two explanations for these tongues seem plausible.

1. The particles are eroded from the bottom in the vicinity of the saddle at 85°W and are injected by lateral mixing into the bottom water coming from the pass near the coast.

2. The particles are eroded in the saddle at 85°W and are transported to the north by bottom water entering the basin over the saddle.

Until more direct current meter measurements are available it is difficult to say exactly what the relationship is between the observed distribution of suspended matter and the long-term mean abyssal circulation. One recent estimate of the settling rate of a 5-μm sphere of density 2.65 in sea water (0°C, 34%) is 1.17×10^{-3} cm/sec, or about 370 meters per year [*Gibbs et al.*, 1971]. Since Laird's estimate of renewal time for the basin was about 175 years, if a particle of this size is transported to a region where there is no upward-directed turbulent flux of particles from the bottom, it will settle too rapidly to be of any help in determining the mean circulation in the basin.

The significance of the light-scattering measurements relative to circulation is also difficult to evaluate. In view of the fact that no particles smaller than 2.22 μm were examined in the Coulter counter analyses, the good correlation between light scattering and particle concentrations shown in Figures 2–6 indicates that either the particles smaller than 2.22 μm do not contribute significantly to the scattering measurements (which would be true if there were few of them or if they had low indices of refraction) or else the factors which influence the observed distributions (e.g., erosive forces, advection, diffusion) affect both the larger and smaller particles in a similar way. In any event, the scattering measurements lead to the same conclusions about particle sources and sinks and circulation as do the Coulter counter measurements. It would seem to be important in the future to extend our size distribution measurements to smaller particles and to utilize any available techniques that provide information on the composition and index of refraction of the particles.

In conclusion, the observed distribution of particulate matter in the Panama basin has in general confirmed the pattern of abyssal circulation suggested by *Laird* [1971], although it does appear that the saddle at 85°W longitude is a site of reasonably high-energy dynamic processes. However, we cannot evaluate precisely, on the basis of our measurements, the contribution of these processes to the supply of bottom water to the basin.

Since the work done in this study was concentrated around the two saddles in the Carnegie Ridge, the particle distribution in the northern part of the basin is as yet not well defined.

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